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ULTRASONIC CHARACTERIZATION OF SYNTHETIC SOILS FOR APPLICATION TO NEAR SURFACE GEOPHYSICS

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ABSTRACT

Effective seismic interrogation of the near subsurface requires that measured parameters, such as compressional and shear velocities and attenuation, be related to important soil properties. Porosity, composition (clay content), and fluid content and identification are of particular interest. The ultrasonic (100-500 kHz) pulse transmission technique was used to collect data for highly attenuating materials appropriate to the vadose zone. Up to several meters of overburden was simulated by applying low uniaxial stress of 0.1 MPa to the sample. The approach has been to make baseline measurements for pure quartz sand, because the elastic properties are relatively well known except at the lowest pressures. Second phases are then added to modify the sample microstructure and ultrasonic measurements are made to characterize the effect of the admixed second phase. Samples are fabricated from Ottawa sand mixed with a swelling clay (Wyoming bentonite), and with a common organic soil amendment, peat. Compressional (P) velocities are low, ranging from 169 to 360 m/s for the mixtures at low stress. Shear (S) velocities are about half of the compressional velocity, but show different sensitivity to microstructure. Adding clay increases the shear amplitude dramatically with respect to P, and also changes the sensitivity of the velocities to load. These experiments demonstrate that P and S velocities are sensitive to the amount and type of admixed second phase, even at low concentrations. Other properties of the transmitted signals which include the ratio of S and P amplitudes, velocity gradient with depth, and the frequency content of transmitted pulses, provide additional information and are not now used in near-surface surveys.

INTRODUCTION

Surface and cross hole seismic methods are now a standard tool for site characterization (Steeples, 1998). Seismic surveying and imaging are being used to address a broad variety of engineering, environmental and ground water problems. Typical applications include locating perched water tables, tracking fluid movement in the subsurface, and delineating landfills. Measured seismic properties have been available for many years and are used in a wide variety of applications including geotechnical (Whitman, 1966), sediment acoustics (Hamilton and Bachman, 1982) as well as basic studies of porous media (Wylie et al., 1958). Unfortunately, relating the measured seismic attributes to material properties and composition is difficult for environmental problems because of gaps in measurements for appropriate media under controlled laboratory conditions.

For example, measurements at low pressure representative of the first 10 meters depth are not available because of extremely high attenuation. Measurements are sparse for partially saturated soils, again because of high attenuation. Shear wave measurements in general are more difficult because the arrival is obscured by earlier compressional energy. Although it is widely appreciated that clay content of a mineral soil is an important factor in controlling the seismic attributes, the coupled mechanical and chemical effects expected for clays have not been investigated in detail. The effect on seismic properties of organic components of mainly mineral soils are poorly known. The purpose of the work described in this paper is to begin addressing some of these shortcomings in the literature and to develop more effective methods for extracting soil properties, such as water content and soil composition, from field seismic data.

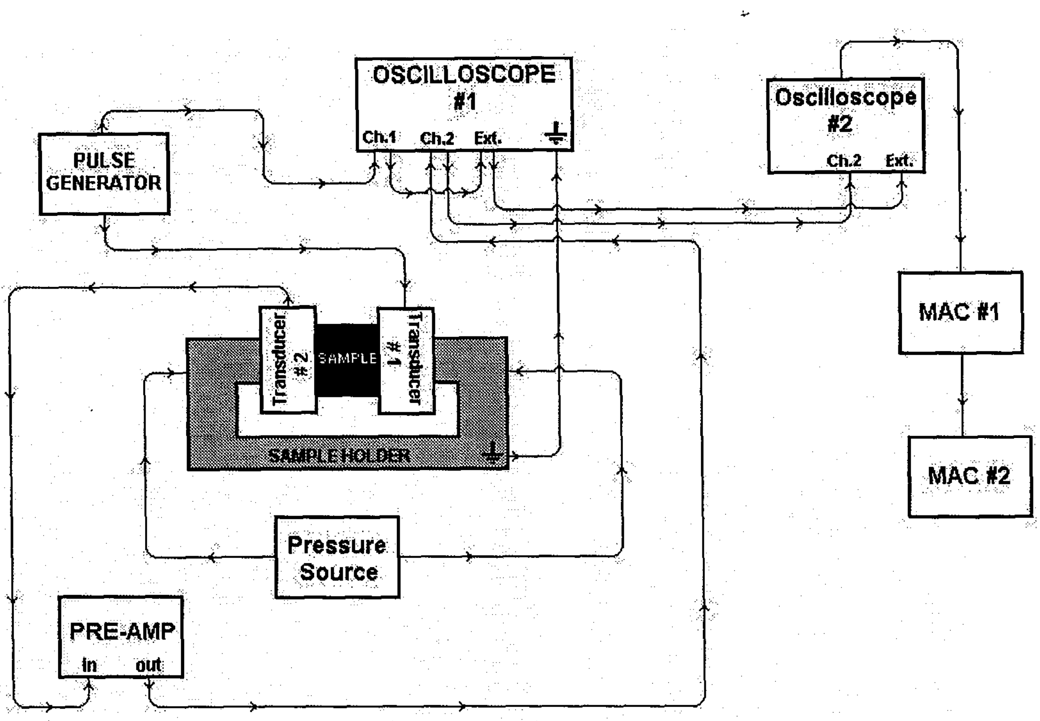

Figure 1. Schematic of the ultrasonic pulse transmission system, including the assembly for applying uniaxial load.

EXPERIMENTAL APPARATUS AND PROCEDURES

The experimental method (Fig. 1) is based on ultrasonic pulse transmission, modified from Sears and Bonner (1981). The time-of-flight of an ultrasonic pulse launched from a transmitting to a receiving transducer and the sample length (44.9 mm) yields the velocity for the appropriate phase. Stress induced changes in the path length produce small changes in travel time compared to concurrent changes in the elastic constants and are neglected here in velocity computations. Transducers with center frequencies ranging from 100 to 500 kHz polarized for transverse shear were used for measurements. Although the peak energy of received signals was lower because of severe attenuation, sufficient high frequency energy is transmitted to sharpen the first arrival. The transducers are not mode pure and produce some compressional energy so that both compressional and shear velocities can be determined simultaneously.

Improvements on the standard methods were made to allow measurements of weak arrivals. The transmitting transducer was driven at 400 V. Received signals were as small as 10^{-5} V, requiring amplification of 60 db for detection. Signal averaging 1000 repetitions improved the signal-to-noise ratio sufficiently to pick arrivals. A sample sleeve was constructed to ensure that the signal travels through the soil mixture, eliminating energy on traveling longer, but faster, paths to the receiving transducer. The sample assemblies were closed with latex membranes which transmitted sound from the transducer and contained the soil mixture. Accuracy was limited to 20% at the lowest stresses but improved with signal amplitude to ~3% for compressional waves and 10% for shear waves at higher stresses. Some of the data scatter is caused by differences in subjective picking of arrivals, as well as dramatic changes in the character of the waveforms with stress. Software is under development to process the signals so that more consistent picks can be made, both manually and automatically.

End-load pressures between 0 and 15 psi (0 to 0.11 MPa), simulating up to several meters of overburden, are applied in increments of approximately 1.5 psi to the sample by air-driven, pneumatic istons that push on the transducer housing. Although the sample sleeve is not perfectly rigid, the internal stress in the sample approximately corresponds to the uniaxial strain condition.

Samples were constructed by mixing pure quartz sand with either clay or peat moss in increasingly larger percentages by weight. The sand was quarried near the city of Ottawa, Illinois, and was sieved to a median grain diameter of 273 micrometers. The clay is Na-montmorillonite from Wyoming, a swelling smectite. The clay is equilibrated in a 100% humid atmosphere for seven days before sample preparation to achieve reproducible water content. The peat is Canadian sphagnum peat moss with a polyoxalkylene glycol (8 PPM) wetting agent, added by the supplier. Peat moss is readily available commercially and is composed mainly of natural cellulose fibers. Typical organic content of peat moss is 80 to 95% of the mass fraction. The peat was equilibrated with air at ambient humidity, typically 30%, before sample construction.

The samples were layered to include a central section of pure sand to be consistent with earlier experiments (Bonner et al., 1997), which used the high permeability layer to provide access for pore fluid. Quantitative interpretation of the ultrasonic data requires corrections for the sand layer, which is ~10% of the length for sand-clay samples and ~30% for sand-peat. Ultrasonic properties depend only in detail on the layered structure. Qualitative interpretation and relative comparisons between samples are valid. Packing methods affect the ultrasonic measurements, as will be discussed in the Results section.

RESULTS

Representative waveforms for Ottawa sand and sand with 3% clay are presented in Figure 2 to give a general idea of the quality of the data and to demonstrate the dramatic effects of composition and microstructure. The upper trace shows a waveform for dry sand with the shear pulse peaking at approximately 240×10^{-6} s. The amplitude ratio of shear to compressional pulses is ~1.7. When 3% clay is added, the shear pulse grows in relative amplitude and sharpens indicating higher frequency content. The s to p amplitude ratio is ~4.5. Both observations are consistent with a relative decrease in shear attenuation. The third waveform shows the effect of water saturation. The details of saturation effects, including the effect of pore fluid chemistry on clay bearing samples, are beyond the scope of this paper, but the changes relative to a dry sample are dramatic. The compressional velocity has increased by a factor of 4 to 5 to approximate the velocity for water, 1.5 km/s. The compressional wave dwarfs the shear arrival, which is difficult to determine and has diminished to near the amplitude observed in the dry sample. When saturated, the sample behaves acoustically similar to a suspension.

Velocities for sand-clay and sand-peat mixtures are plotted in Figure 3 to illustrate that velocities are low and increase rapidly with small static loads. It is important to point out that two different pure sand samples were used for comparison to the mixtures. The first, compared with the sand-clay samples, was densified by vibrating during fabrication. Although this method produces the most efficient densification, it was later abandoned because vibrations destroyed the high permeability sand layer discussed above. All mixtures and subsequent standard pure samples were prepared by hand packing. The hand packed sand sample, compared in Figure 3 to the peat mixtures, has lower compressional velocities at all stresses than the vibrated sample, although the difference is diminished at the highest stress. Although the hand packed sample has a slower shear velocity than the vibrated sample at the highest stress, the trend is reversed at lower stress. Additional experiments or re-examination of the stored waveforms will be needed to better understand the effect of packing.

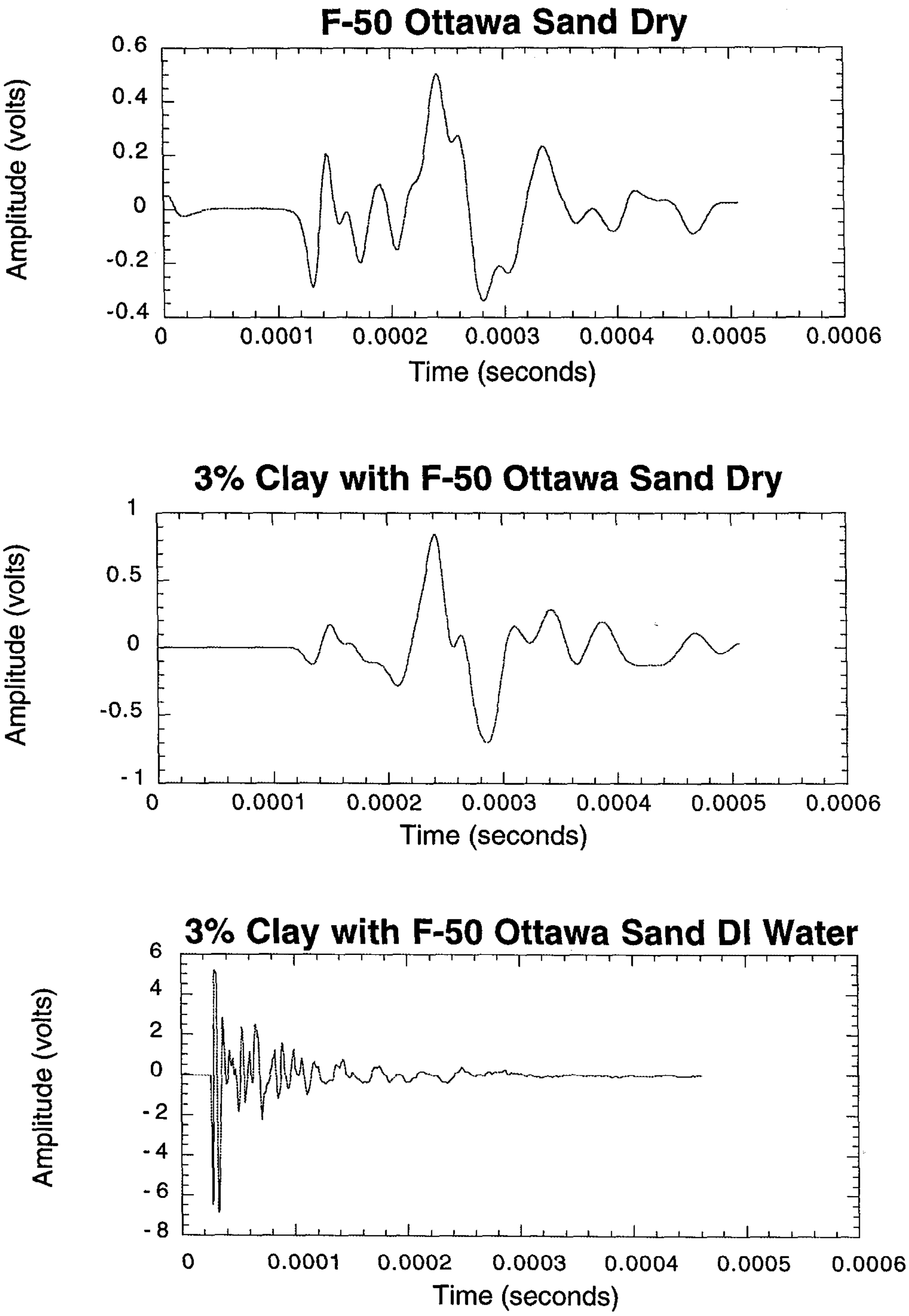

Figure 2. Received ultrasonic pulses for top:) dry sand; middle:) three percent clay-sand dry; and bottom:) three percent clay-sand saturated with de-ionized water.

Although the behaviors shown in Figure 3 are complicated, several dominant trends are evident. The stress sensitivity of the sand velocities is altered by the addition of small amounts of clay. Compressional velocity of sand-clay at all concentrations is essentially constant until the stress exceeds 8 psi, when it increases at a rate similar to the pure sand. It appears that the clay binds the sand grains until a critical stress is exceeded, and then yields and flows away from regions of local high stress at grain contacts. This behavior appears to persist to the highest clay fraction tested, 40%. In contrast, velocities of the peat mixtures remain stress sensitive, and in some cases may increase more rapidly than the pure sand. The 20% peat sample shows a very large change in compressional velocity, which may be an artifact of the very high attenuation observed for this mixture.

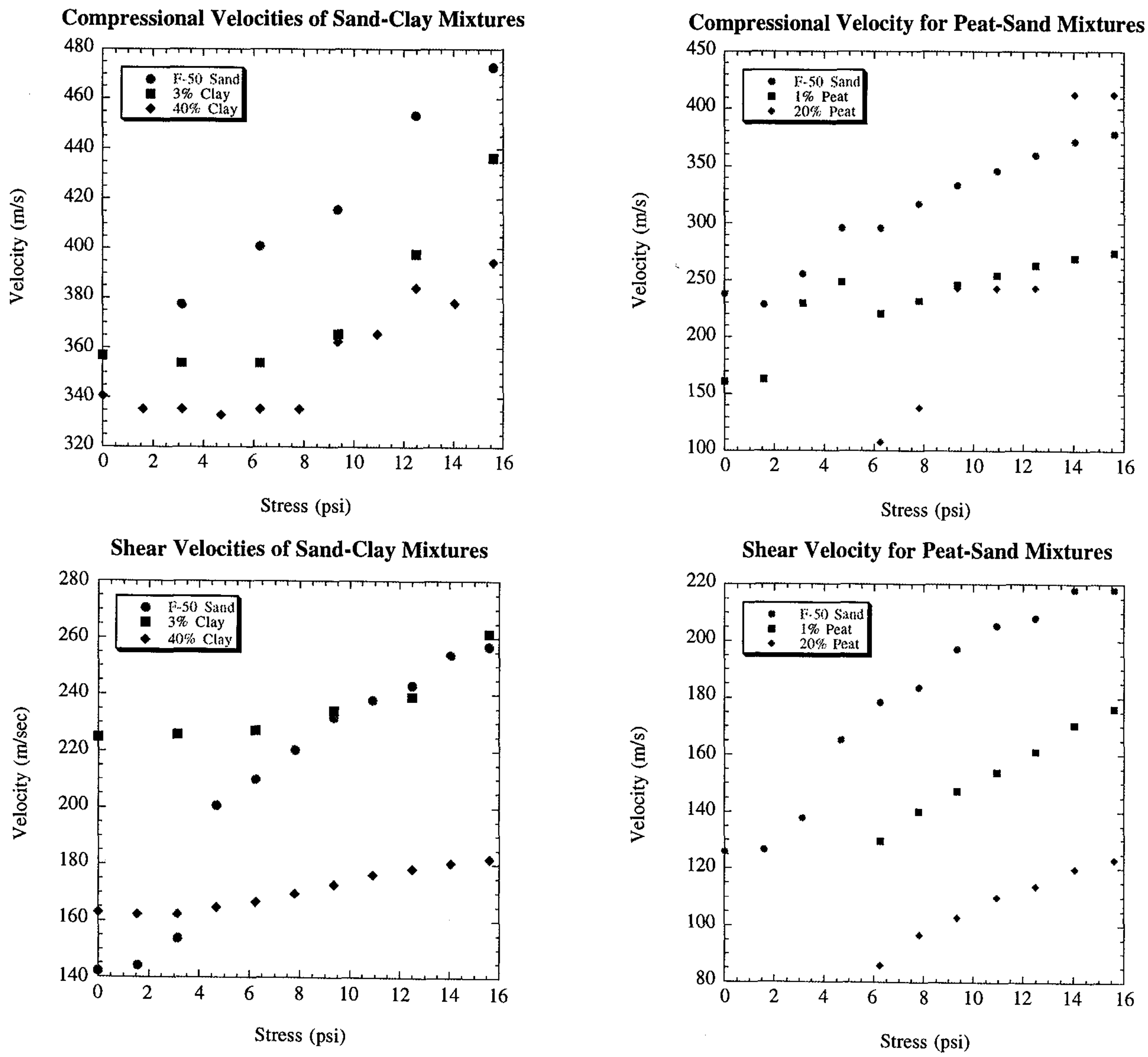

Figure 3. Uniaxial stress dependence of compressional and shear velocities for representative sand-clay and sand-peat mixtures.

The velocities are not simple functions of added second phase. The plots of Figure 4 show the variation of velocities for both mixtures at low and high loading stress. When data from the hand-packed pure sand sample is used as a reference, it is apparent that the first addition of clay to sand increases the compressional velocity. This increase persists at high stress. The shear velocity is less sensitive to the first addition of clay and decreases slightly, although the amplitude increases (Figure 2). Compressional velocity decreases when the clay content is increased to 10%, although this effect is reduced by additional stress. The shear velocity reaches a maximum at 10% clay concentration, and additional stress does not suppress the behavior.

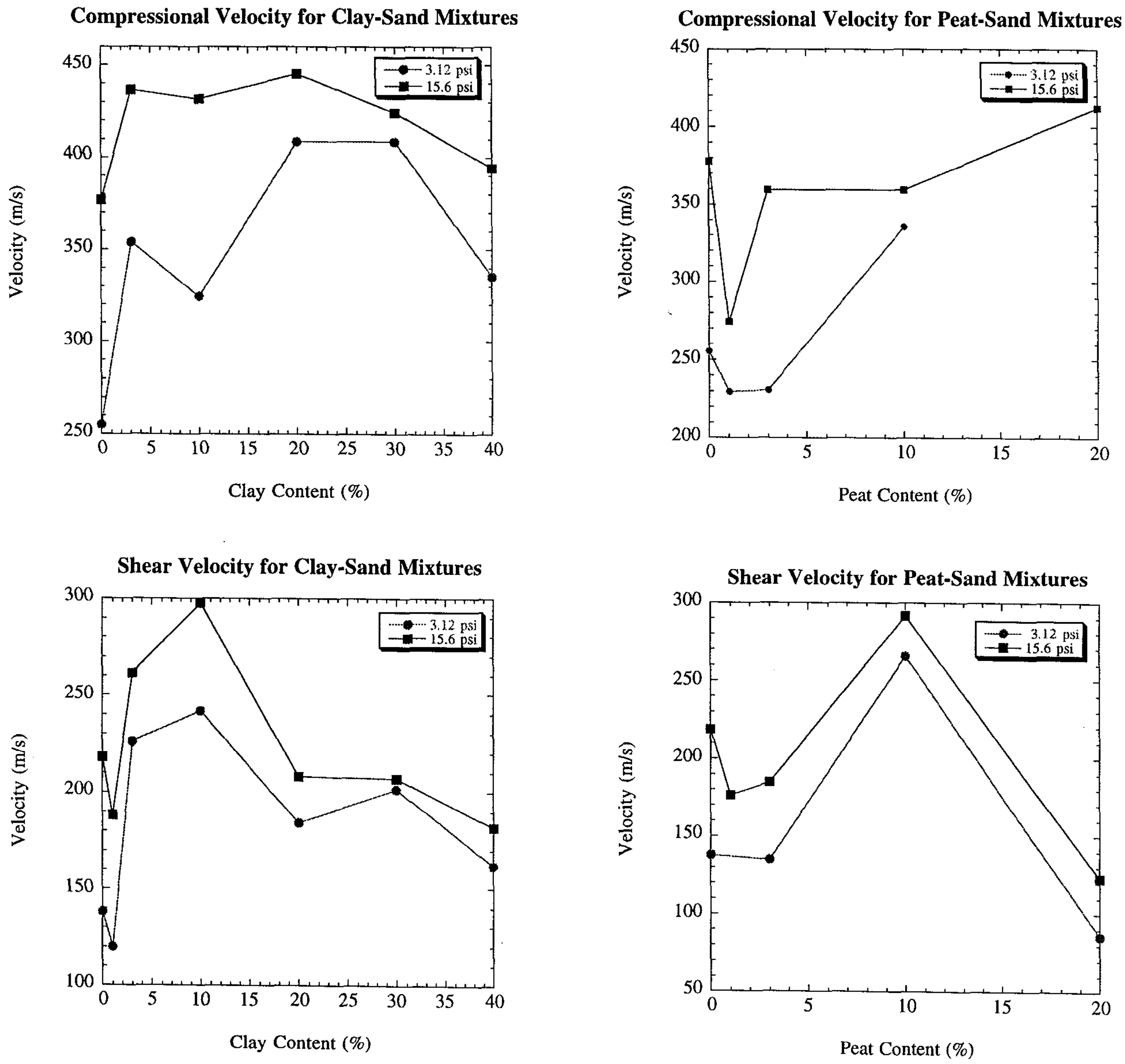

Figure 4. Ultrasonic velocities for two different loads as a function of added second phase.

Velocities for the peat-sand samples are low. For comparison, the speed of sound in air is 330 m/s. Both velocities decrease with small amounts of second phase, but then increase. Changes in the shear velocity are less sensitive to the stress. The apparent high velocity of the 20% mixture at the highest stress is surprising considering the high attenuation at this peat concentration, and the apparent large decrease in shear velocity. Further refinements of the experimental technique may be needed to investigate specimens with high peat concentrations.

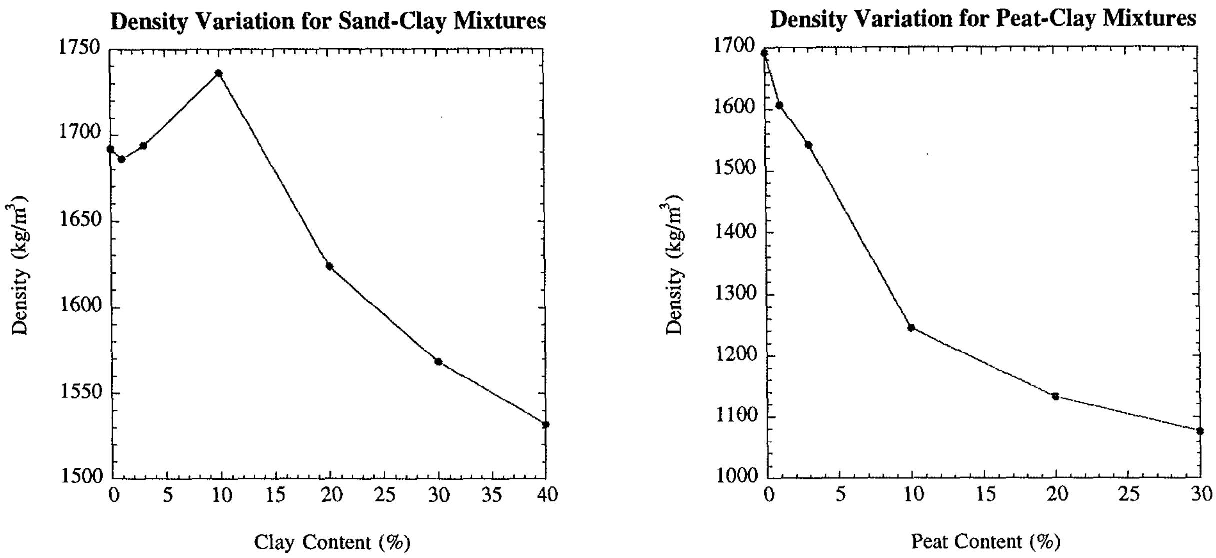

Figure 5. Bulk density as a function of added second phase for sand-clay and sand-peat mixtures.

The density of both mixtures as a function of added second phase is plotted in Figure 5. Density for sand-clay reaches a maximum at 10% when sufficient clay has filled the open pore space. The maximum corresponds to the maximum in V_S of Figure 4. The density of the sand-peat mixtures continuously decreases as more peat is added. Below 10% mass fraction, the change is most rapid because peat (with a density of ~1 gm/cc, (Telford et al., 1976)) displaces air from the sample. Above 10%, peat displaces quartz, and the slope decreases. The density plots show that the mixtures behave as three component systems composed of quartz, open pores and a second phaseconsisting of clay or peat, which are porous solids.

DISCUSSION

The velocities observed for the synthetic soils tested in this study are low, with a compressional velocity comparable to the sound speed in air for the slowest sand-peat mixtures. The compressional velocities are lower than typical field values as compiled by Bourbie et al., 1986 and are slightly higher than values for near-surface sand reported by Bachrach et al., 1998b. The admixed second phase can alter seismic attributes even for low mass fractions. The photomicrograph of sand-10% clay spread on a glass slide shown in Figure 6 suggests that the micromechanics of the small clay particles may explain this strong influence. The clay particles adhere electrostatically to the quartz grains with their long axes perpendicular to the surface and tend to bridge the gaps between quartz grains. The large increase in compressional velocity when clay is first added to sand accompanied by a decrease in shear attenuation suggests that the clay alters the grain contacts by acting as an adhesive. In contrast, peat does not increase the velocity at low concentration, but immediately causes both velocities to decrease. The clay mixture shows the same decreasing behavior after the initial increase. It appears that at this stage the soft second phase disrupts the structure of the sand framework causing a decrease in velocity.

As the mass fraction of the second phase continues to increase, porosity reduction dominates, generally producing the highest velocities. Finally, when the free porosity is eliminated, velocities begin to drop as the slow second phase becomes the framework. This behavior is similar to that reported by Marion et al., 1992, for sand-kaolinite mixtures at high pressures.

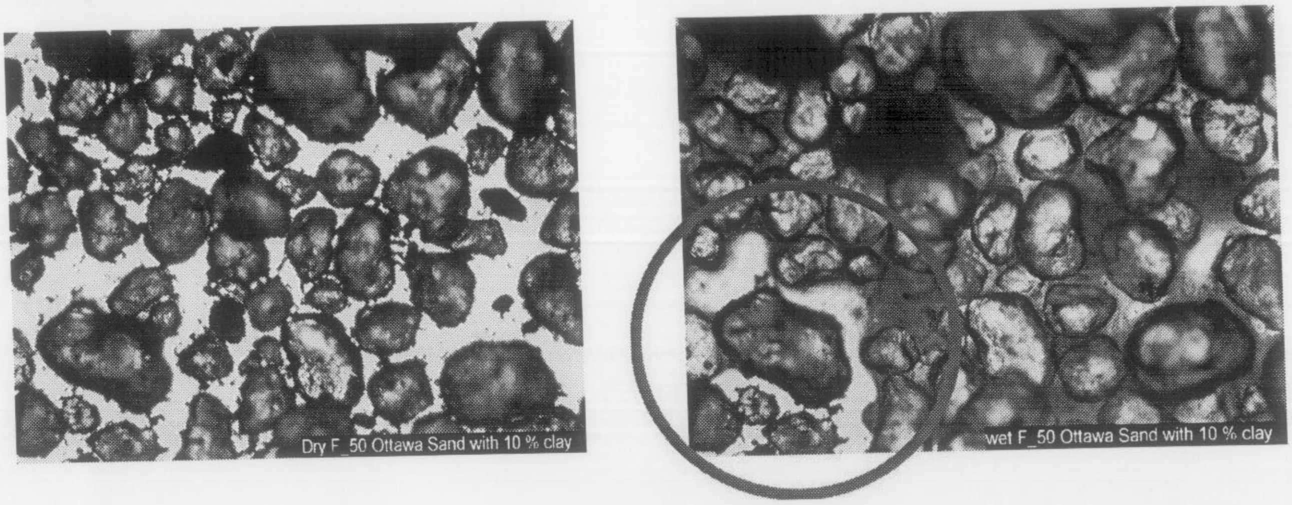

Figure 6. Photomicrographs of sand with ten percent clay. The grain size of the sand ranged from 74-420 microns with a mean of 273. The mixture in the left photograph is dry. The right photograph shows fluid advancing into the mixture. The circled area shows the boundary between fluid and gas phases.

Compressional velocity is a multi-valued function of the concentration of the added second phase and porosity for these soil mixtures. Additional information must be used to extract composition and porosity, parameters critical for predicting the hydrological properties of the near surface. Work currently underway by Berryman et al. (1999) suggests that simultaneous measurements of p and s produce more robust porosity estimates for a wide range of materials. Shear to compressional amplitude ratio may prove to be a useful indicator of clay in the vadose zone. Quality shear measurements are now being made in the field (Carr, et al., 1998). The changes in the pressure dependence of velocity when clay is added suggest that low velocity gradients observed in field data may be useful indicators of clay bearing, low permeability zones.

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